DEVELOPMENT OF CRITERIA AND STANDARDS FOR VEHICLE COMPATIBILITY

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ABSTRACT

This paper summarises the results of a project on vehicle crash compatibility, run by European automotive industry together with some research institutes. The project was funded by the European commission as BE97-4049.

There are three main issues that can be detected in real world accidents, influencing vehicle compatibility. These issues are mass differences, compartment integrity with regard to frontal car-to-car impact, and differences in bumper and sill height in side impact. Longitudinal mismatch in frontal impact, front end stiffness and other items which are from a theoretical point of view responsible for vehicle aggressiveness are not seen influential from the view point of real world accidents.

On the other hand, compartment collapse occurs, when there is not sufficient deformation energy available in vehicle front-end. And deformation energy is available, when it is provided by vehicle structures and when these structures interact. So compartment collapse can only be avoided, as long as sufficient deformation energy is available and is effective within the car-to-car collision.

So the paper will provide results with regard to the questions of deformation management. It will give guidelines for future research on compatibility, which has to focus on the problem of structural interaction.

GOAL

In vehicle-to-vehicle crashes, two vehicle safety viewpoints have to be considered (Figure 1):

- **Self-protection**, the ability of a vehicle to protect its own occupants, both in vehicle-to-vehicle accidents and against other objects in the traffic environment.
- **Partner-protection**, the ability of a vehicle to protect the occupants of the opponent vehicle in vehicle-to-vehicle crashes.

The intention of this project was to minimise fatalities and injuries in the vehicle fleet by taking into account self and partner protection. It was aimed to develop common design rules to achieve an optimum structural interaction of vehicles. This goal should be reached by requirements on implications of vehicle structure like restricted force levels, dummy loads etc.; it is not understood as a restriction of the design possibilities. It should be achieved as far as possible by computer simulation with finite element models (FEM). The knowledge should be summarised in a suggestion for a procedure for an enhancement of compatibility of the vehicle fleet that could lead to a European standard. The **Compatibility** of a vehicle is understood as a combination of self- and partner protection in such a way that optimum overall safety is achieved, this is regardless of in which vehicle the injuries or fatalities occur. It is not acceptable to compromise today's self-protection level.

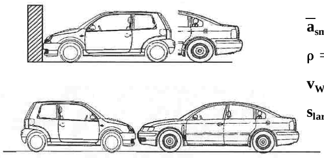
Conflict of goals between Self- and partnerprotection

or

between **deformation travel** of large vehicle and

mean acceleration of small vehicle

$$\bar{a}_{small} = 1/2 * \rho * v_W^2 / s_{large}$$



$\bar{a}_{small}$ = mean acceleration small vehicle

ρ = mass ratio of vehicles

v_W^2 = rigid wall test speed

s_{large} = deformation travel large vehicle

Figure 1: Conflict of goals in compatibility

ACTIONS

Two steps were taken to reach this goal:

- **Accident analysis** was conducted using accident databases from Germany, France, Great Britain, Sweden and Finland. Variables that might be relevant with regard to self and partner protection were considered.
- **Car-to-Car and barrier impact analysis** including
  - <u>Crash tests</u> were conducted to study the findings of accident analysis and derive criteria for the evaluation of vehicles.
  - <u>Computer simulation</u> was conducted to achieve a deeper understanding of the effect of variables considered and to study, whether it is possible to substitute crash testing for the evaluation of crash compatibility.

ACCIDENT ANALYSIS

The factors were rated as compulsory when they have a clear influence on compatibility. They were rated as possible, when an influence was not seen or not clearly seen in accident analysis but when other reasons were found to study this effect more deeply by crash tests and computer simulation (Table 1).

Variable	**Importance** based on accident analysis	**Importance** taking into account accident analysis, crash tests and computer simulation
Mass	**Compulsory**	**Frontal impact: Not considered, unchanged** **Side impact: Minor relevance, unchanged**
Front-end stiffness	Possible	Enable sufficient deformation energy up to a defined force-level
Compartment stiffness	**Compulsory**	**Compulsory proved**
Lateral fork effect	No effect	→ Structural interaction
Vertical fork effect	No effect	→ Structural interaction
Lateral longitudinal mismatch	No effect	→ Structural interaction
Vertical longitudinal mismatch	Possible	→ Structural interaction
Override of sills	**Compulsory**	**Compulsory proved**
Homogenous front-end	Possible	→ Structural interaction
Engine orientation	Possible	Unchanged
Corner impact	Special case	Unchanged

Table 1: Compatibility factors derived from accident analysis

The accident databases that were studied consist of mainly older vehicles. These vehicles have older generation restraint systems, a significant number have no airbags or pretensioners and are unlikely to be have been designed for the offset deformable crash test.

Only three of the issues that were highlighted in the list were found to be clearly relevant from the viewpoint of accident analysis.

Vehicle mass is a well-known influence factor in vehicle-to-vehicle crashes. It was decided that it was infeasible to affect vehicle mass with regards to compatibility. A mass ratio of 1.6 covers 80% of the European passenger vehicle-to-vehicle accidents and defines a range within which vehicle compatibility can be improved, if a self protection level of a rigid barrier impact speed of approximately 56 km/h is considered.

Vehicle-to-vehicle frontal accidents with fatalities or serious occupant injuries were mainly accidents with severe **deformation of the passenger compartment**. In severe accidents involving older vehicles high occupant decelerations and severe compartment intrusions result from loading of the compartment. These two effects cannot be discriminated by accident analysis.

Accident analysis found that **front-end stiffness** was not relevant but from a theoretical understanding of vehicle impacts it was rated as a 'possible' variable. The fact that this variable was not found in accident analysis is surprising and from a theoretical point of view questionable. This observation might change, when a fleet of stiffer vehicles exists and can be analyzed.

Fork effects - undeformed longitudinals intruding into an opponent vehicle - were observed only in a very small number of cases in accident statistics. However, cases of structural **mismatch** - different vertical or lateral position of load paths of colliding vehicles - were observed. In some statistics, it was found that mismatch in a vertical direction is an advantage or at least no disadvantage. This finding was not expected. A possible explanation is that in the majority of less severe accidents a mismatch is an advantage because it leads to lower force levels and thus to lower decelerations. In more severe accidents mismatch may be a disadvantage because it might lead to higher deformations. Due to the smaller number of more severe accidents in the databases this would explain the finding from accident analysis.

IMPACT ANALYSIS: FRONTAL IMPACT

Compartment Stiffness (Resistance)

Accident analysis results showed that **compartment stiffness** (resistance) was one of the main compatibility issues. Crash tests were performed to understand compartment **overload**. High-speed crash tests (so called destruction tests) were conducted with various small cars to overload the passenger compartment and investigate its deformation resistance well beyond the elastic limit. Time histories of acceleration and force measurement on a load cell wall were studied. Depending on the vehicle structure and engine position there were significant differences between the vehicles.

One of these small cars was used to study repeatability. In three similar tests against an offset deformable barrier (ODB) with a high EES (~74km/h) different intrusion patterns and structural forces occurred (Figure 2).

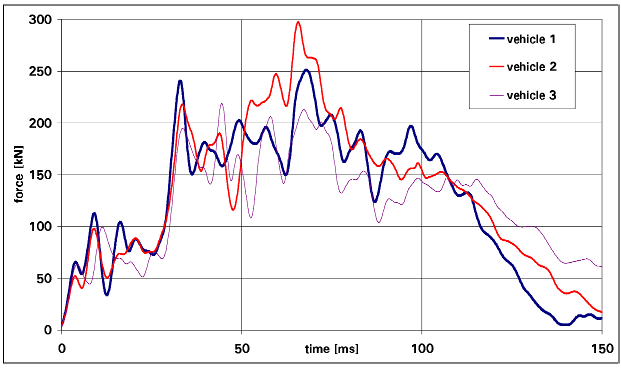


Figure 2: Structural forces from destruction tests with identical cars

Two further tests with this car were conducted at 64 km/h against an ODB. The force deflection curves derived from compartment acceleration for these tests are similar (Figure 3). This kind of test reflects an energy equivalent speed (EES) of 55...60 km/h. In this test most today's vehicles retain structural integrity. The maximum force detected in both of these tests was 250 kN. This is also the average maximum force level for the series of the three destruction tests with this car, although the values show a high scattering. In a vehicle-to-vehicle crash test with this car, the force level of 250 kN was also achieved.

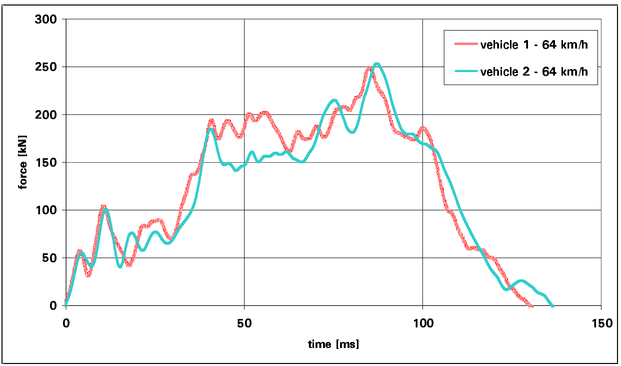


Figure 3: Structural forces (mean B-pillar acceleration * affiliated mass) from 64 km/h ODB test for identical cars as in Figure 1

The conclusion is that within the severity range of 64 km/h ODB test the maximum reproducible force level of vehicle structure of this car and possible some other vehicles can already be detected. This force level is identified with **compartment stiffness,** which in fact is a **compartment resistance (strength).** The maximum compartment resistance will be detected in different tests and at different speeds for each car. The destruction test is a valid tool for a research study of the compartment resistance, but it is not suitable for compliance or rating purposes.

Front-end Resistance

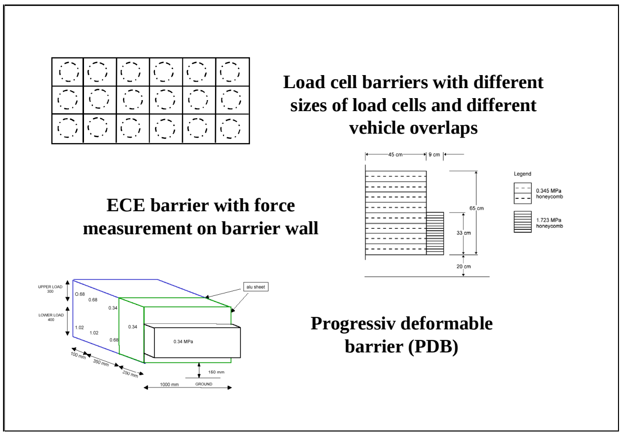


Figure 4: Different barrier types to measure front-end stiffness (resistance)

A series of tests was conducted against the Progressive Deformable Barrier [PDB], which has a progressively increasing force level and an upper and lower difference in stiffness. This barrier has a depth of 700 mm and is designed to avoid bottoming out. The test speed is 60 km/h to avoid reaching self-protection force and the overlap with the vehicle is 750mm to generate always the same force resistance. This barrier and the chosen test condition avoid bottoming out. The final deformation of PDB and the force-deflection curves can be analyzed to see whether the front-end is homogenous or if local differences in stiffness exist. Further research has to provide information which barrier type provides sufficient information with regard to front-end resistance (Figure 4).

VEHICLE-TO-VEHICLE TESTS

A **prediction of the deformation** in frontal vehicle-to-vehicle crash tests was made in accordance with the following rules: ① The force deflection curves of both vehicles from 64 km/h barrier impacts were compared. When theoretically computing the outcome of a vehicle-to-vehicle collision in most cases one vehicle has to provide more deformation energy than in a 64 km/h ODB test. This vehicle may be overloaded, which means that more significant intrusion into the passenger compartment occurs when compared to the 64 km/h ODB test. ② The PDB barrier test maximum force measured on the wall behind the deformable barrier was used to predict the loading on the passenger compartment of the opponent vehicle. The homogeneity of the barrier at the end of crash was generally evaluated under the viewpoint of structural interaction. The predictions held as shown in the following Table 2.

Test	**64 km/h ODB test Prediction**	**PDB Prediction**	**Outcome**	**Structural interaction**
Rover 75 vs. Renault Clio	Clio overloaded	Clio overloaded	Clio overloaded	Rover overrode Clio
Rover 75 vs. Volvo S80	Rover more intrusion	N/A	Balanced impact (S80 more intrusion than Rover)	Good interaction but high loading on A-pillar of S 80
Rover 75 vs. MCC Smart	Balanced impact	N/A	Smart overloaded (higher test speed than intended with theoretically 18% higher energy absorption)	Poor structural interaction. Rover longitudinal directly loaded Smart A-pillar
Rover 75 vs. VW Polo	Polo overloaded	Polo overloaded	Polo overloaded	No over-/underring
Rover 75 vs. Opel Astra	Astra overloaded	Balanced impact	Balanced impact (Astra and Rover had more intrusion than in the 64 ODB test)	Good structural interaction, Astra subframe was incorrectly modified.
Opel Astra vs. Renault Clio	Clio overloaded	Balanced impact	Balanced impact	Good structural interaction

Table 2: Predictions and results of frontal vehicle-to-vehicle tests

Two findings were made from the analysis of these vehicle-to-vehicle tests:

- The total force measured behind the deformable element can not be used as an indication how the vehicle will perform in vehicle-to-vehicle tests. It is necessary to distinguish between the mechanical parts forces and the structural forces (Figure 5). The force measured on the barrier is the sum of mechanical parts forces (mainly engine/transmission impact) and the structural forces (Figure 6). The mechanical parts and structural forces can be calculated by multiplication of the acceleration of these parts with the associated masses. Deformation management has to consider the front end and structural forces of both impact partners.
- The result of the car to car tests show that the outcome predicted from an assessment of deformation management can be wrong due to a lack of structural interaction. The PDB approach might be able to predict this.

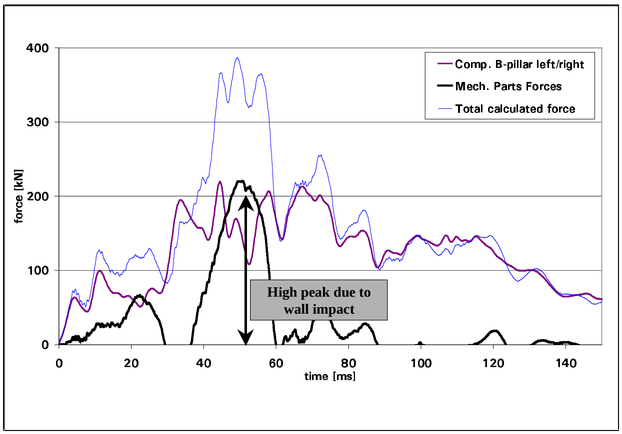


Figure 5: Comparison of structural forces (compartment) and mechanical parts forces

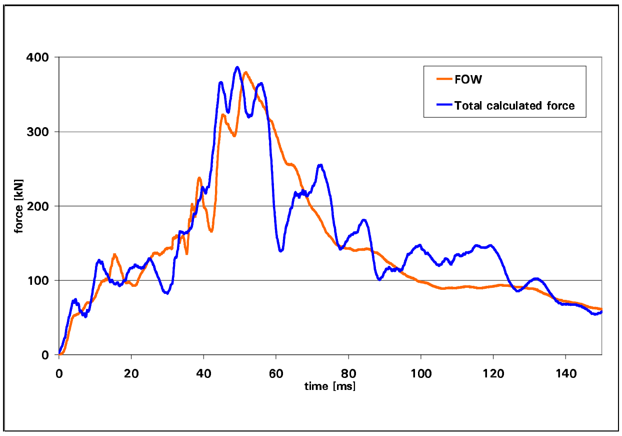


Figure 6 Comparison of measured wall force and total calculated force

Structural Interaction

Mismatch of load paths and 'Homogenous front end' initially 'excluded' or rated as 'possible' have to be combined and reassessed due to the importance of **structural interaction** found in severe frontal vehicle-to-vehicle crashes**.**

The outcome of CAE and test investigation emphasized that importance. Identical impact partners were used. Although they have optimal interaction conditions (same mass, same geometry and the same stiffness due to the alignment of longitudinals), they react differently depending on the vertical mismatch of longitudinals compared with the case of matching longitudinals. In these cases not all designed load paths were activated.

Due to this fact, the requirement can be deduced that the energy absorbing structural parts of the impact partners have to interact in a controlled and predictable manner. That is the prerequisite for every requirement dealing with stiffness and energy absorption.

Avoiding overriding completely, as an important part of structural interaction, will be difficult because 30mm height difference of the centerline of longitudinal cross sections already leads to partial over-/underriding. Therefore additional front-end measures (devices) to avoid over- and underriding in severe impacts have to be investigated (Figure 7, Figure 8).

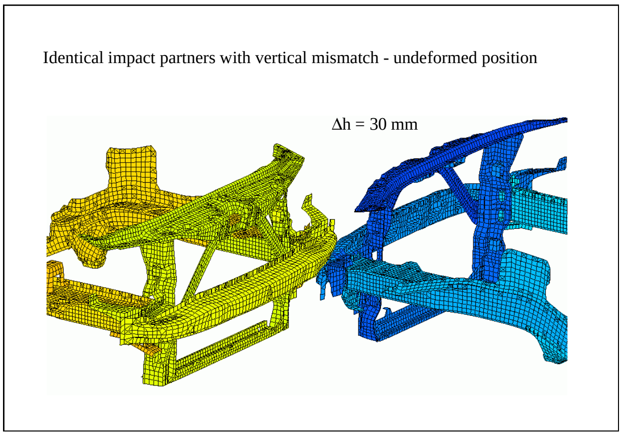


Figure 7: Identical impact partners with height difference before crash

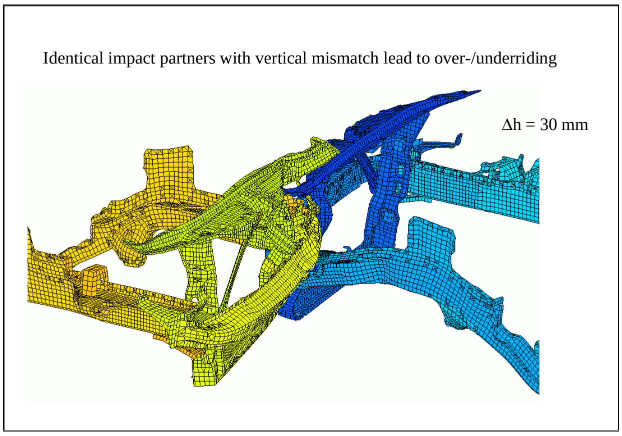


Figure 8: Over-/Underriding due to vertical mismatch

IMPACT ANALYSIS: SIDE IMPACT

Regarding side impact various parameter variations were conducted. In vehicle-to-vehicle side impacts the mass of the bullet vehicle is of less concern but the height difference between the struck vehicle sill and the bullet vehicle bumper is a more relevant issue. This is fully in line with the findings from accident analysis. Crash tests and simulations proved that when the longitudinals hit the sill of the target car substantially lower dummy loads are generated, although this might be difficult to achieve, which have to be further investigated.

In identical side impact tests with the mass of the bullet vehicle increased by 300 & 600kg there was no clear effect of increasing severity for the occupants of the struck vehicle.

Two tests were conducted with an identical target vehicle and two bullet vehicles with different initial front-end stiffness' derived from AZT (Test defined by German insurance companies). The crash with the lower initial front-end stiffness resulted in lower dummy loads in the target vehicle. This finding might be influenced by side effects like structure and geometry, which were not identical in both bullet vehicles.

A comparison was made of a lateral 90° impact and an angled impact into the side of the same struck vehicle. The results showed that the increase in severity in the case of an angled impact was not as great as expected. However, the bullet vehicle struck the target vehicle at the 'A' pillar and there was good interaction between the structures which mitigated the severity of the impact.

COMPUTER SIMULATION

As part of the project, computer simulation for compatibility investigations was used. To describe the possibilities of the Finite Element Method (FEM) the following impact modes must be distinguished:

- Barrier tests in the range where the vehicle retains its structural integrity
- Barrier tests in the range where the vehicle loses its structural integrity
- Vehicle-to-vehicle impacts

In general, FEM is a valid tool to predict vehicle behavior, although it is not yet able to simulate material failures like tearing of spot welds or detachment of structural parts.

Barrier tests are mainly used to design vehicles. As long as the vehicle deformed in a range where it retains its structural integrity, computer simulations are used as a tool to predict the vehicle performance. A validated model is necessary as a basis of such work.

In barrier tests that overload the structure (destruction tests) more material overload occurs. So, the general weakness of FEM prevents its use in destruction tests. The lack of repeatability in the overload tests reinforced that statement because whenever crash tests are not reproducible, computer simulation, which produces 100% reproducible results, cannot predict the scattering, and of course cannot predict a result of the single crash test, which is unique. Simulations done within the project proved that statement. Even when a vehicle is not overloaded in **vehicle-to-vehicle impacts** more material overload and sliding effects occur than in barrier impacts that are used to design the vehicles. The usage of FEM is, therefore, limited. The work done in the project shows that FEM computer simulation is able to reproduce vehicle-to-vehicle testing with respect to:

- the major effects of the crash and
- the amount of deformation and its characteristics.

Validation by a base line test is necessary. Good correlative quality of deceleration traces requires a great deal of effort and depends on the occurrence of sliding effects and local overload. They can vary from case to case and this limits the prediction quality.

The general weaknesses of FEM can not be solved as part of a compatibility project. They have to be addressed by methodological work like the EU funded project "Virtual testing", coordinated by TNO.

CONCLUSION

Frontal Impact

- The following variables were found to be relevant for frontal vehicle compatibility
  - Mass
  - Structural interaction (containing fork effects, mismatch of structural parts, homogeneity of the front end)
  - Deformation management (passenger compartment and front end stiffness)

  Structural interaction and deformation management have to be investigated further with respect to their potential for standards and requirements. Mass differences within the vehicle fleet are a consequence of customer demands. Therefore changing the mass differences of the vehicles is not possible. A mass ratio of 1.6 covers 80 to 90 % of European vehicle-to-vehicle accidents.
- Deformation management of the front-end and the passenger compartment should be described by resistance (deformation forces) rather than by stiffness.
- To avoid overcrushing of the opponent vehicle, the front-end resistance (deformation force) of the striking vehicle should be lower than the compartment resistance of the struck vehicle.
- High-speed 'destruction' tests do not necessarily provide more information regarding compartment resistance than the 64kph ODB test. Due to possible irreproducibility they might provide misleading results.

- Structural interaction and deformation management are required for compatibility. Deformation management is covered by the bulkhead concept, which means (Figure 9):
  - Sufficiently high force level of the compartment to ensure survival space
  - Restriction of the front-end resistance to force levels sustainable by the compartment resistance of the opponent vehicle and taking into account opponent vehicle acceleration
  - Ensuring this relationship up to a mass ration of 1.6, which covers 80 to 90 % of European vehicle-to-vehicle accidents

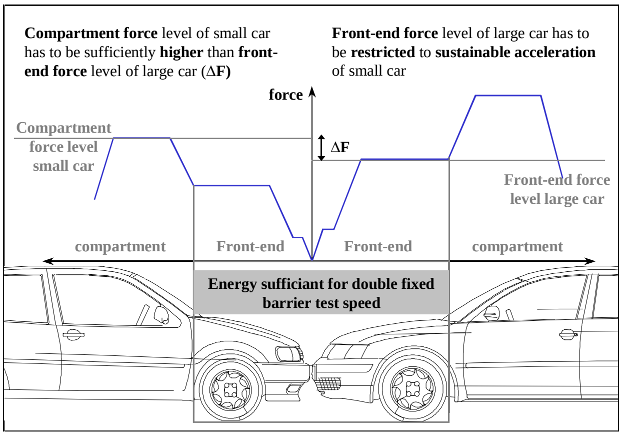
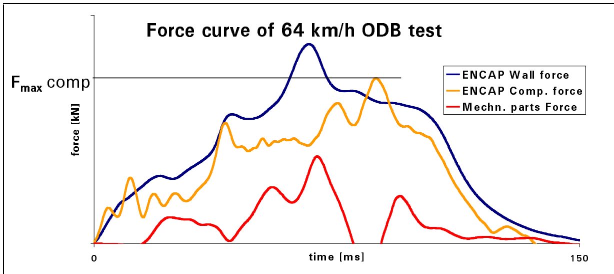


Figure 9: Bulkhead concept

- Within the severity range of EES 55...60km/h, computer simulation is an adequate predictor of vehicle crash behavior against barriers. It is not able to predict tearing of material or welding joints/spots. Until the CAE tools are improved, their use in vehicle-to-vehicle tests is limited.
- Force deflection curves of frontal impacts of a vehicle, which retains its structural integrity, provide some information about compartment resistance and the deformation energy available for partner protection. This information is valid only if load paths interact. The force deflection curves separated for mechanical parts and the passenger compartment in frontal impact ODB crash test with the vehicle retaining its structural integrity provide some information about the compartment resistance and the deformation energy of the vehicle front-end which is available for partner protection (Figure 10). This energy is only available and thus valid for evaluating partner protection ability, if the geometrical preassumptions hold and if load paths interact properly.



The higher F_{max} of compartment the higher self protection in car-to-car crash.

If for certain vehicles max. force level of compartment is not detected in 64 kph test, a higher crash speed can be choosen for this vehicle in accordance with vehicle design.

Figure 10: Compartment resistance derived from 64 km/h ODB test

- Geometrically, a structural fit of load paths should be created during the crash. Structural interaction must be ensured before high local loads on the compartment occur with the risk of high intrusion into the compartment. The PDB shows the final deformation and its local differences and is a candidate to assess the compatibility of front ends. Further research is needed to fully understand structural interaction.
- Although computer simulation was not able to replace hardware tests it might be valid to study structural interaction if validated models for the appropriate test modes exist. It can be a very useful tool to investigate the details of deformation.

Side Impact

- An override of sills by the bullet vehicle is a disadvantage for the occupant of the struck vehicle.
- The mass ratio is of minor influence.
- The stiffness of the longitudinals as observed in repair cost tests, might influence the load of the occupant of the struck vehicle.

Override of sills and the stiffness of the front end will be influenced by the measures to improve front impact compatibility. These effects have to be considered. When defining the standards and criteria for front impact the implications for side impact compatibility should be studied.

RECOMMENDATIONS

Some of the car-to-car crashes that were performed followed the predictions derived from barrier tests. These predictions were derived from an understanding of deformation management, the compartment resistance of both vehicles and the available deformation energy in the crash. The main reason that both types of prediction failed in particular cases is due to the lack of structural interaction in those impacts.

This leads to the following recommendations:

- Investigation of structural interaction and methods to assess the capability of two vehicles to interact in a frontal and lateral vehicle-to-vehicle crashes.

- Compatible structures need to have sufficient deformation energy available at a 'compatible' force level. Up to a specific severity passenger compartments have to resist the loading that occurs in a vehicle-to-vehicle impact. The front-end and compartment forces that ensure efficient deformation management have to be defined and the appropriate measurement of these forces has to be established in detail.
- Compatibility between the smallest and largest vehicles is probably not achievable due to the contradictory demands of self- and partner-protection. Up to a mass ratio of 1.6, compatibility can be established that holds for 80-90% of the European passenger vehicle fleet.
- Changes to the vehicle front may have implications for side impact. This must be investigated.

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